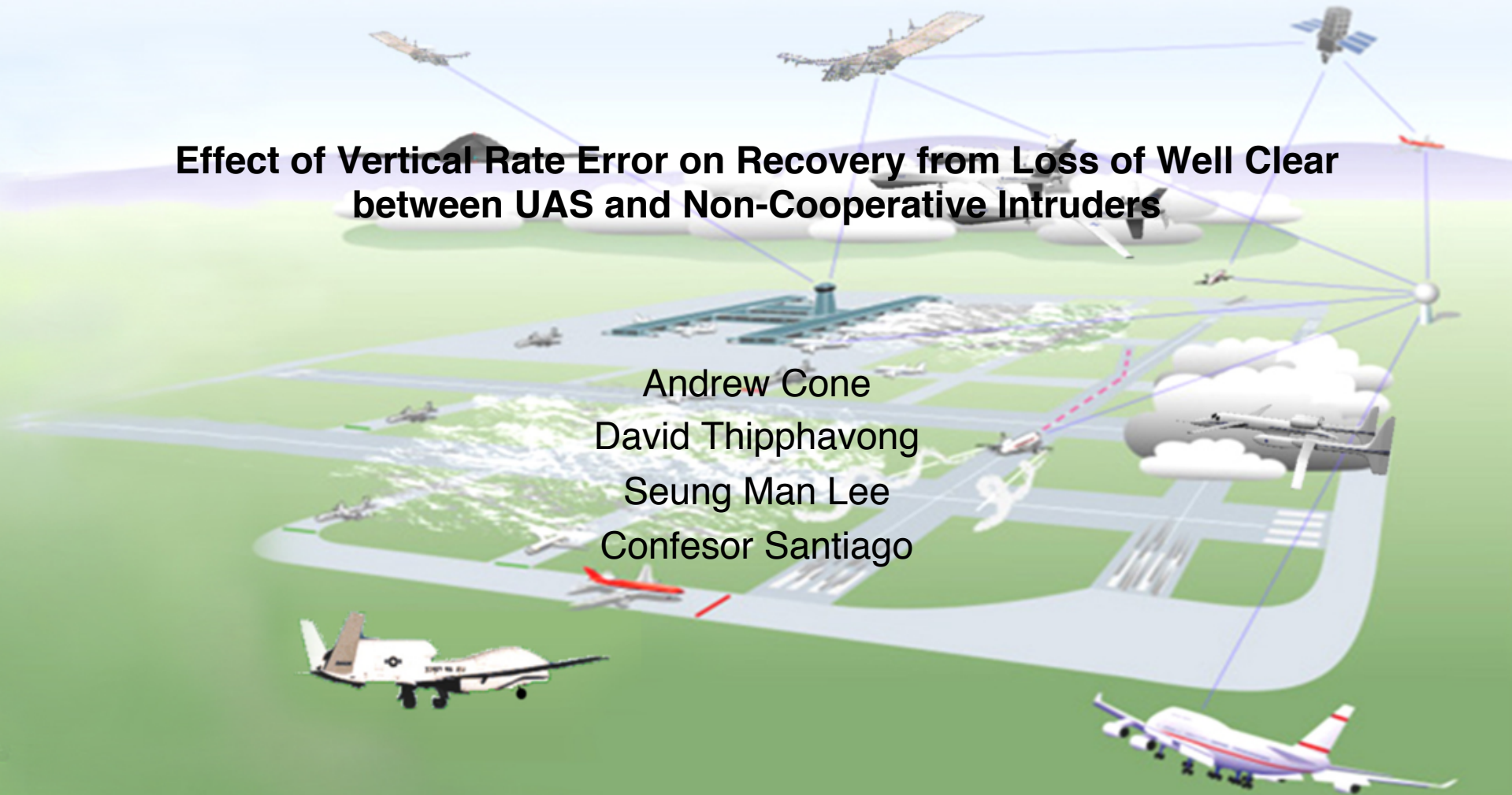


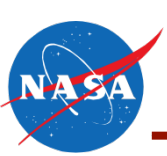


National Aeronautics and Space Administration

Effect of Vertical Rate Error on Recovery from Loss of Well Clear between UAS and Non-Cooperative Intruders

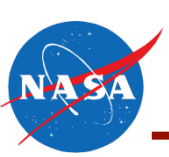
Andrew Cone
David Thipphavong
Seung Man Lee
Confesor Santiago



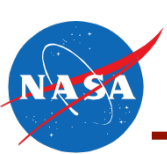


Top level results

- Analysis of safety-critical subset of encounters covered by an RTCA SC-228 requirement showed requirement is overly restrictive and adversely affects safety about 1/3 of the time
- Recommended actions to account for analysis results
 - Include an exception for the safety-critical subset of encounters where requirement is more restrictive than necessary
- OR
- Rewrite requirement to be more flexible, with more responsibility in the hands of UAS manufacturers
- Encourage more research beyond safety-critical subset of encounters evaluated in this study

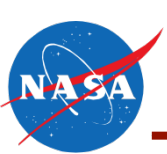


Background



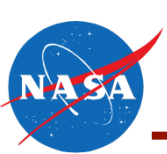
MOPS Requirement to Suppress Vertical Guidance

- NASA conducted a fast-time simulation study to assess the suitability of a MOPS requirement for DAA systems to suppress UAS vertical guidance under certain conditions (see MOPS lines 3576-3581)
- Paraphrased: UAS vertical maneuvers are prohibited when the intruder is non-cooperative, within 3000 feet vertically and at least one of the following conditions is true:
 1. Vertical position error is 175 ft or more
 2. Vertical rate error is 400 fpm or more
- The above conditions would cover nearly all encounters that lead to well-clear recovery



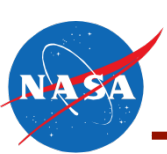
Radar Model Characteristics

- Sensor model provided by Honeywell, with noise tuned to data from a previous flight test
- Range: 13.3 nmi
- Azimuth: +/- 135 degrees
- Elevation: +/- 20 degrees
- Range Noise Mean/Standard Deviation: 5.5 m/10 m
- Bearing Noise Mean/Standard Deviation: 0 deg/0.4 deg
- Elevation Noise Mean/Standard Deviation: 0 deg/0.4 deg



Simulation Overview

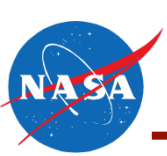
- Mitigated combinatorial simulations of pairwise encounters between UAS and non-cooperative intruders
 - UAS variables: ground speed, vertical performance, turn rate performance
 - Intruder variables: ground speed, heading, climb/descent rate
 - Encounter variables: horizontal and vertical CPA offsets
- Sensor/tracker model
- Pilot model
- JADEM providing guidance via Omnibands



Factorial Encounter Parameters

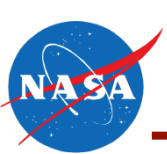
- Two sets of 54,000 simulated pairwise encounters between UAS and non-cooperative intruder

Parameter Type	# Values	Values
Ownship ground speed	2	50, 200 kts
Ownship heading	1	0 deg
Ownship vertical speed	1	0 ft/min (fly level at 9000 ft)
Intruder ground speed	2	70, 170 kts
Intruder heading	5	0, 45, 90, 135, 180 deg
Intruder vertical speed	5	-2000, -1000, 0, 1000, 2000 ft/min
Ownship trial plan maneuver turn rate	2	1.5, 3 deg/sec
Ownship trial plan climb/descent rate	6	(500/500), (1000/1000), (1500/1500), (2000/2000), (500/2000), (2000/500) ft/min
Horizontal intruder trajectory shifting	9	0 nmi: (x,y) = (0,0) 0.2 nmi: (x,y) = (0.2, 0), (-0.2, 0), (0, 0.2), (0, -0.2) 0.5 nmi: (x,y) = (0.5, 0), (-0.5, 0), (0, 0.5), (0, -0.5)
Vertical intruder trajectory shifting	5	-400, -200, 0, 200, 400 ft



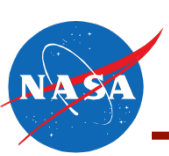
Data Analysis

- Two sets of runs compared:
 - Both horizontal and vertical maneuvers permitted to regain well clear
 - Only horizontal maneuvers permitted to regain well clear
- Focused on subset of encounters in first data set with vertical maneuvers to regain well clear
- Compared severity of loss of well clear to the corresponding encounters in the second data set, all of which were horizontal maneuvers
- Only analyzed encounters with maneuvers at the same time in both simulations to ensure initial conditions (e.g., sensor errors, time to closest point of approach) were the same



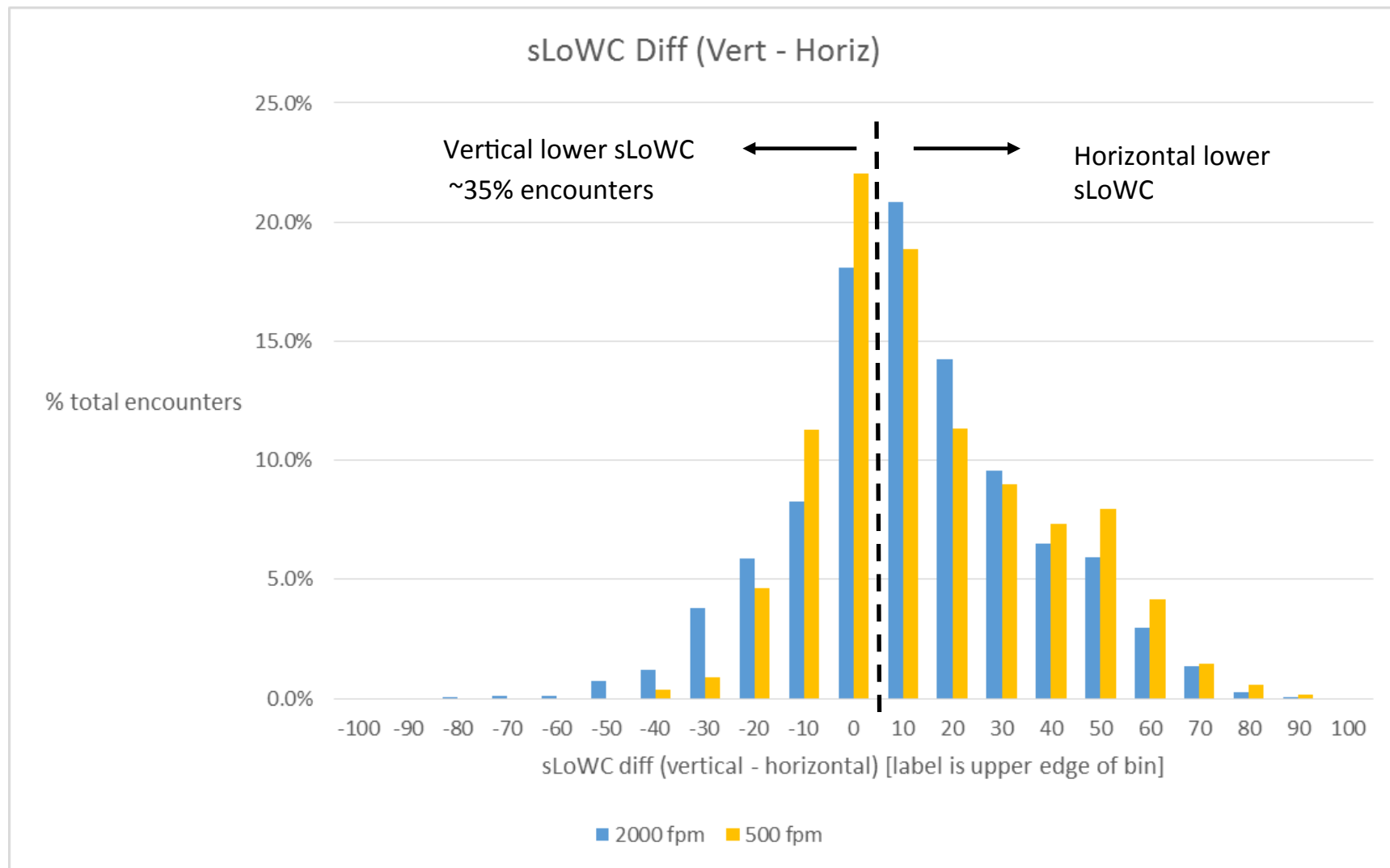
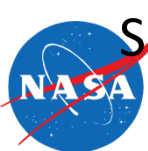
Metrics

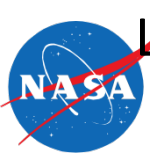
- Primary metric is severity of loss of well clear
 - Derived by Birhle Applied Research Inc
 - Three dimensional separation metric
 - Includes horizontal proximity, projected horizontal miss distance, vertical separation
 - The separation represented by a value changes on encounter characteristics
 - Values range from 0% for barely a loss of well clear, to 100% for encounters with a minimum separation of zero feet.
- Minimum separations for level-level encounter with a relative bearing of 180 degrees:
 - 2000 feet horizontally and colatitude produces max sLoWC of about 44%
 - 1000 feet horizontally and colatitude produces max sLoWC of about 71%
 - 500 feet horizontally and 100 feet vertically produces a max sLoWC of about 73%



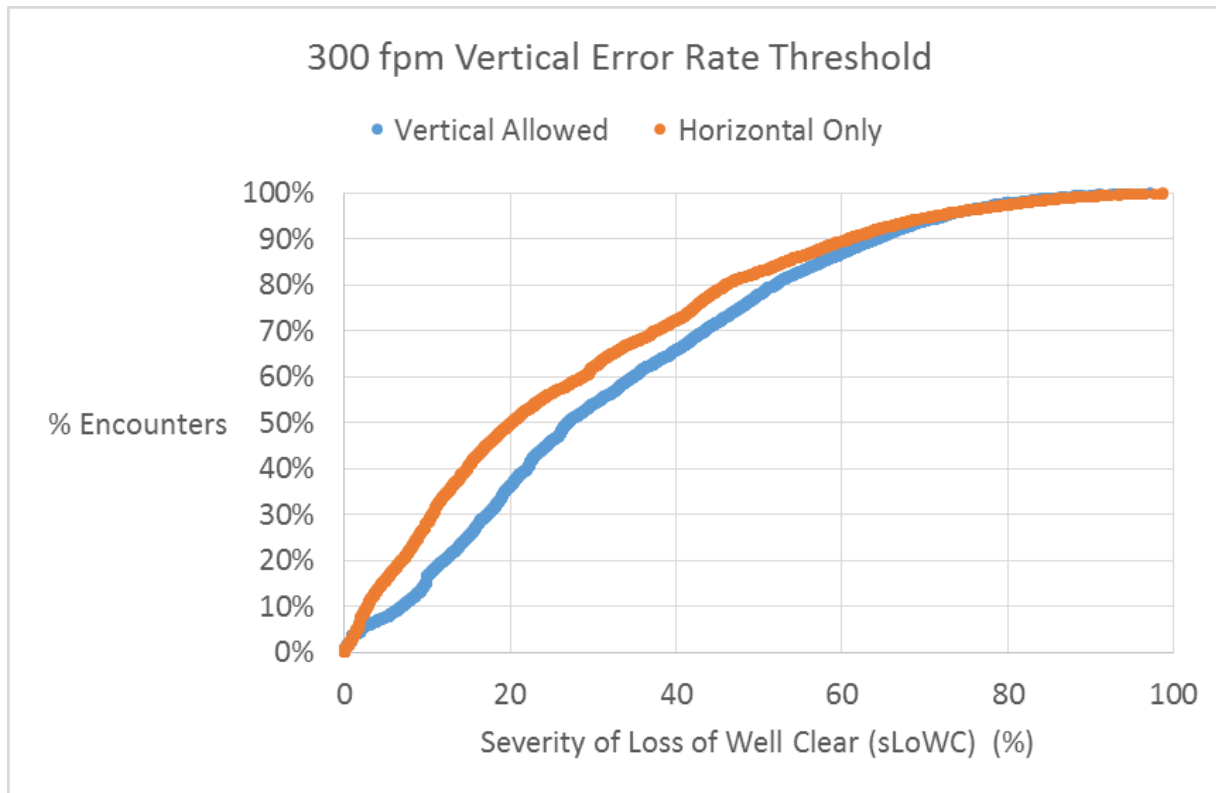
Results

Suppressing vertical maneuvers results in higher LOWC severity in 35% of encounters

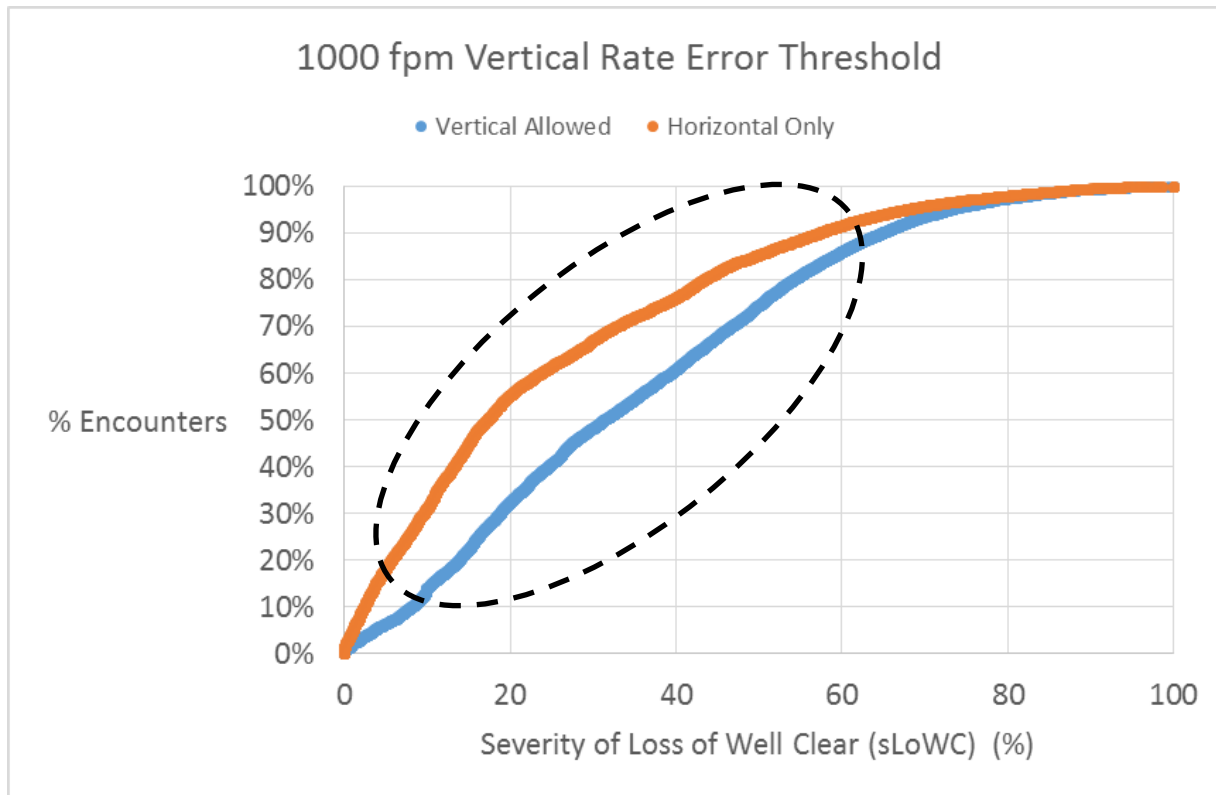


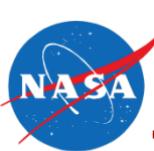


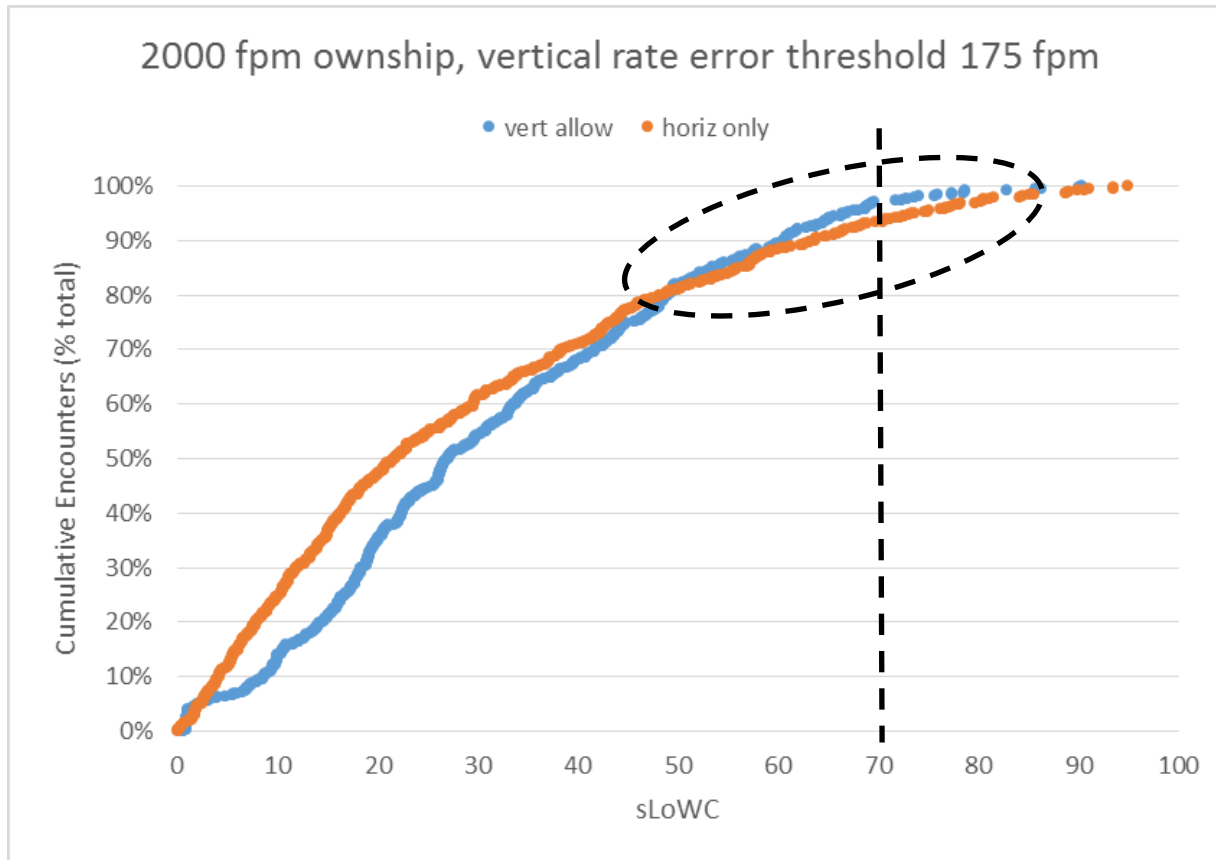
LOWC severity reduced by 3-4% on average when vertical maneuvers are suppressed and vertical rate estimates are good

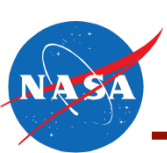


LOWC severity reduced more when vertical maneuvers are suppressed and vertical rate estimates are poor

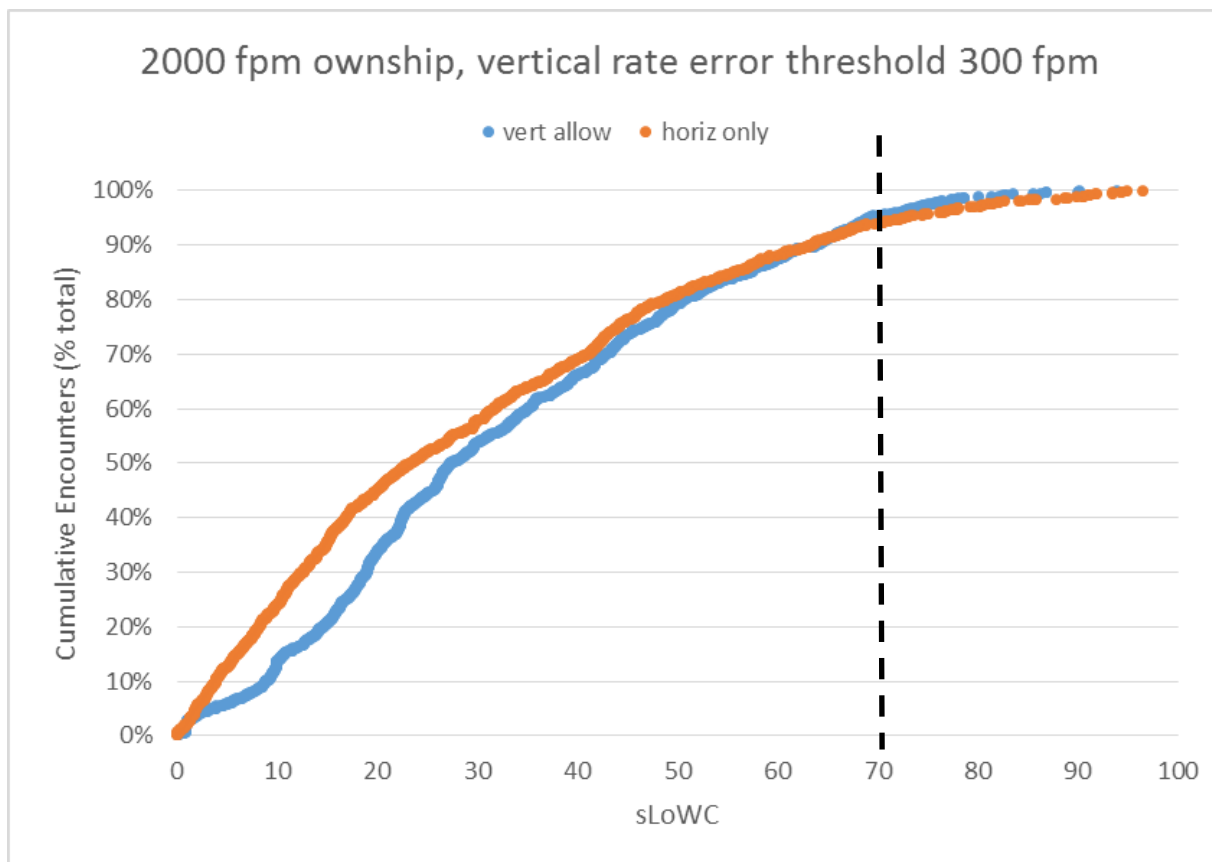


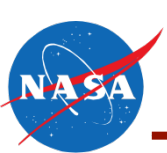
 Allowing high-performance UAS to use vertical maneuvers reduces likelihood of severe LOWC when vertical rate estimates are good



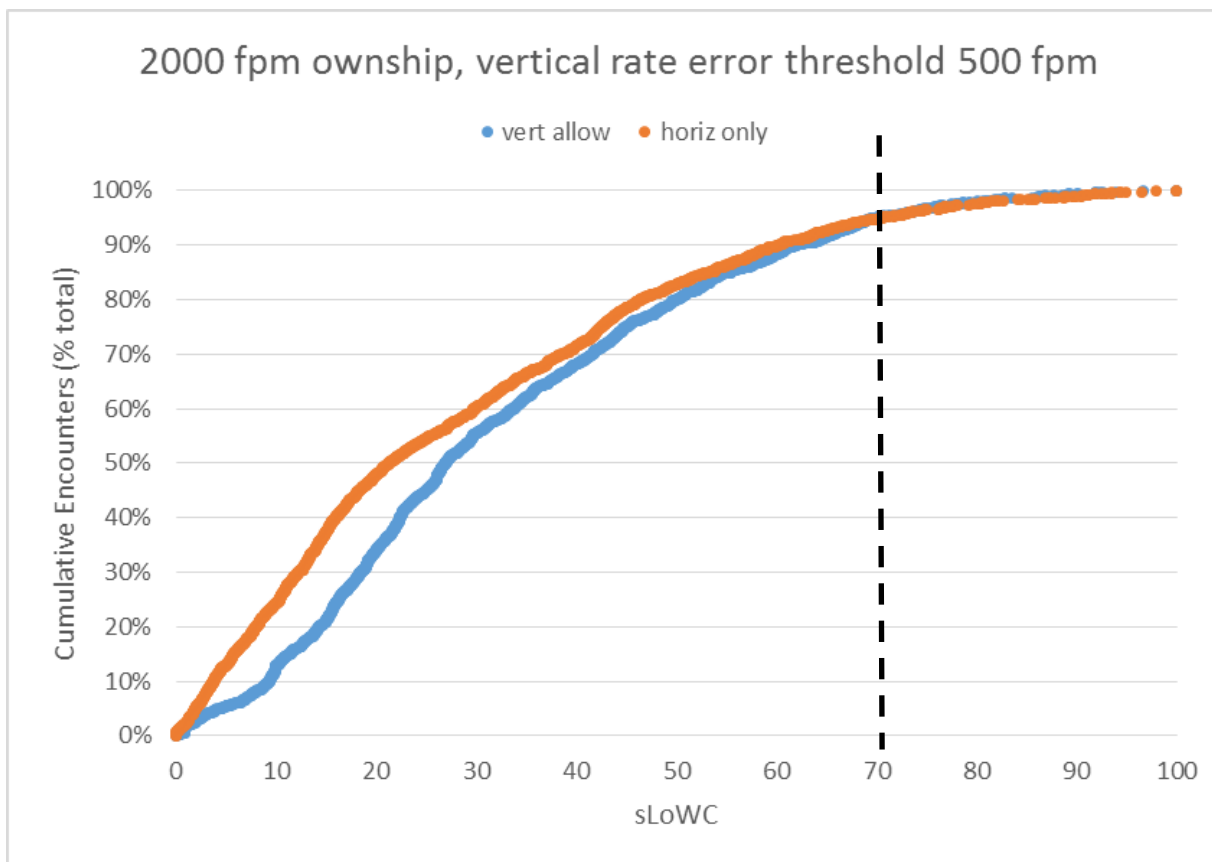


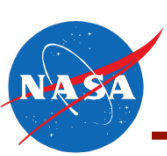
Vertical rate errors negate this





Vertical rate errors negate this





Recommendations

Recommendation #1: Add an exception to current requirement for guidance to regain DAA well clear

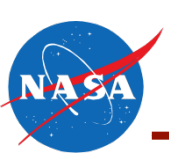
- Suppressing vertical maneuvers resulted in higher LoWC severity in 35% of encounters where a vertical maneuver was preferred

Recommendation #2: Instruct manufacturers to account for ownship performance, sensor error, and encounter geometry when determining whether or not to provide vertical guidance (to regain DAA well clear)


- Allowing UAS with high vertical performance to use vertical maneuvers can reduce the number of severe LoWC, even when vertical rate errors are slightly above the currently proposed threshold

Recommendation #3: Consider further investigation into encounters where there is not a loss of well clear

- Data show a single threshold value is not sufficient to describe when suppressing vertical maneuvers increases safety for aircraft in a LoWC
- Additional testing can show if trends observed in this study appear in all encounters with non-cooperative aircraft, or just the subset that lose well-clear



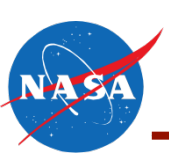
Backup



The number of NMACS decreases when vertical maneuvers are allowed for most UAS vertical performance levels

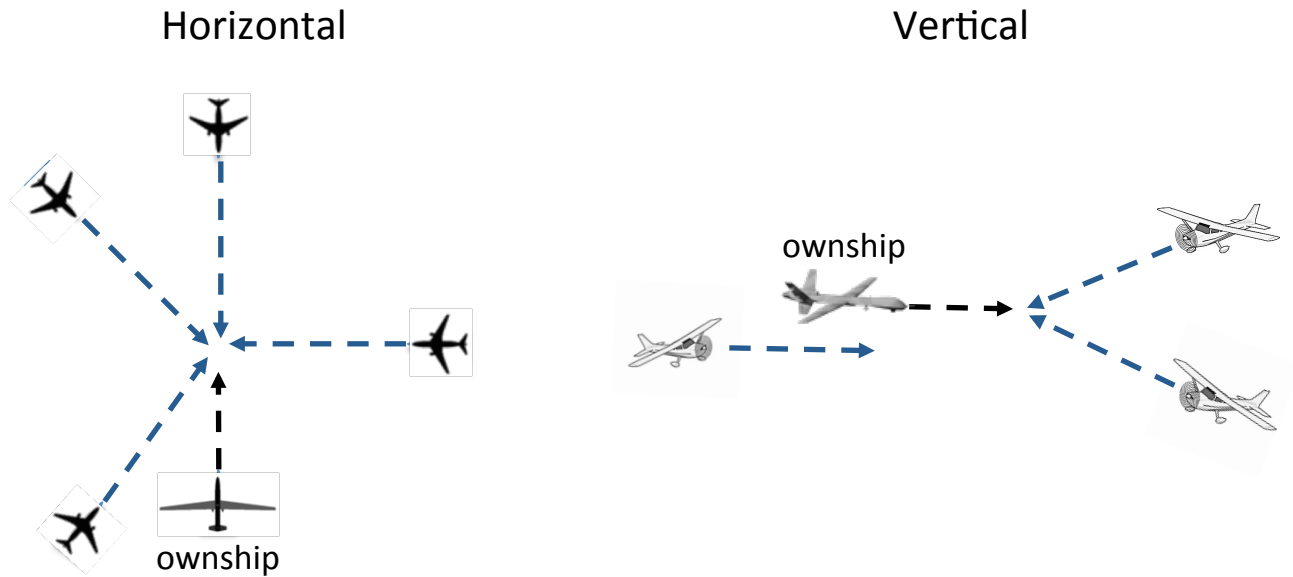
UAS max climb/descent rate	NMAC Difference (Horizontal - Vertical)
2000/2000	90
1500/1500	47
1000/1000	19
500/500	-7
2000/500	74
500/2000	50

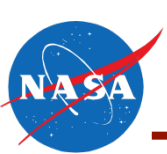
*9000 encounters per scenario



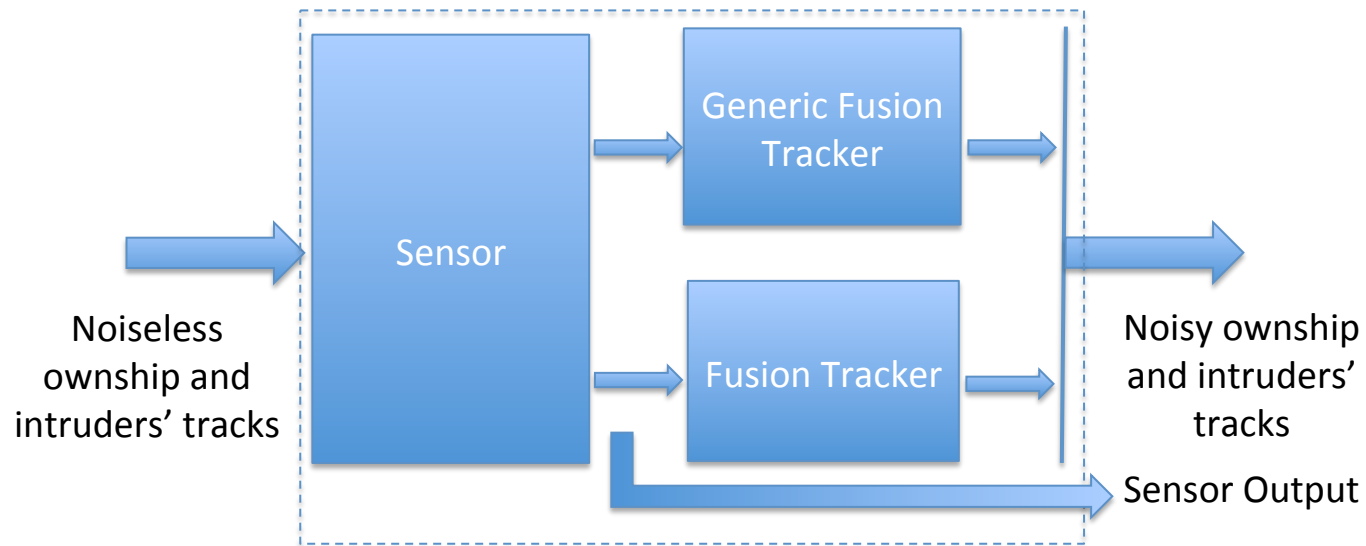
Full factorial module

- Non-accelerating pairwise encounters



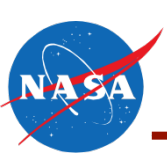


Honeywell Sensor and Tracker Model

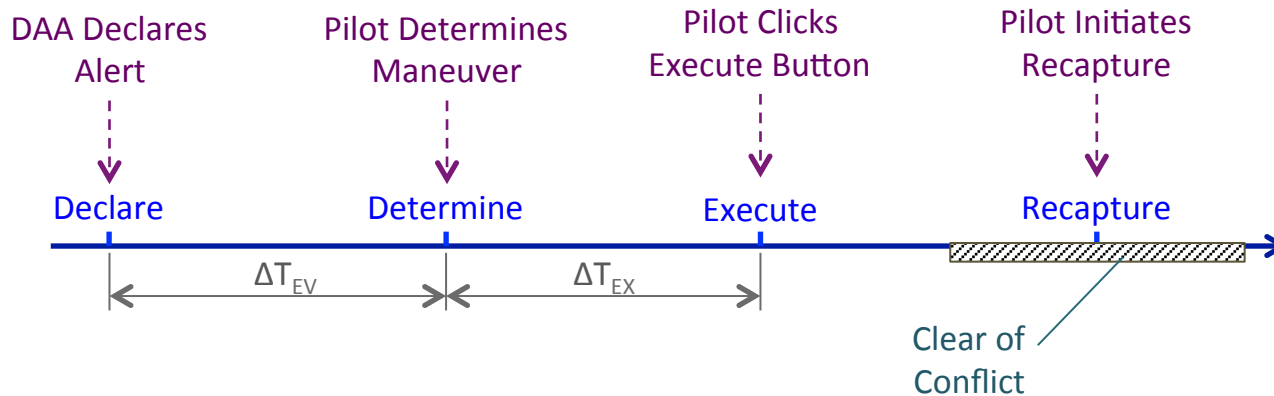


Sensor tracker wrapper

- Sensor model generates realistic sensor noise from ownship and intruder truth tracks
- Sensor parameters selected based on ACAS-Xu flight test data in 2014
- Tracker merges multiple sensor data into tracks



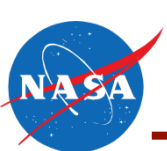
Pilot model



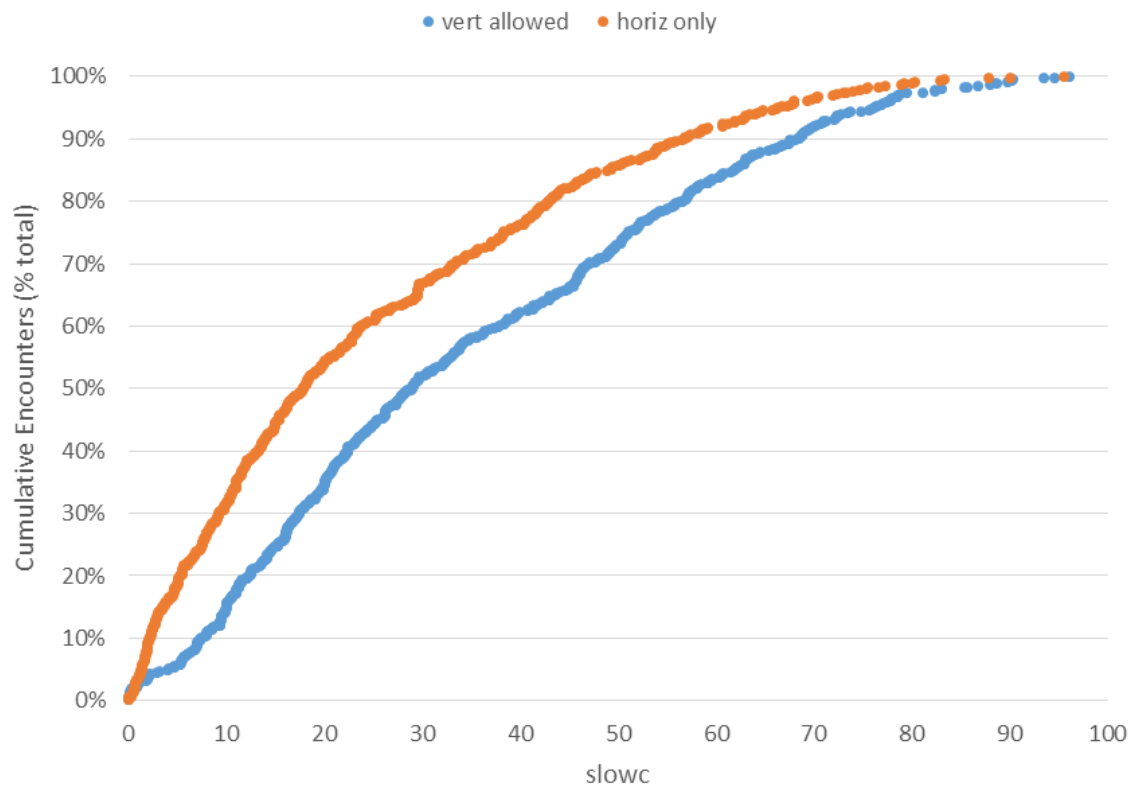
ΔT_{EV} = Pilot Evaluation Delay (Evaluate, Determine, Coordinate Maneuver)

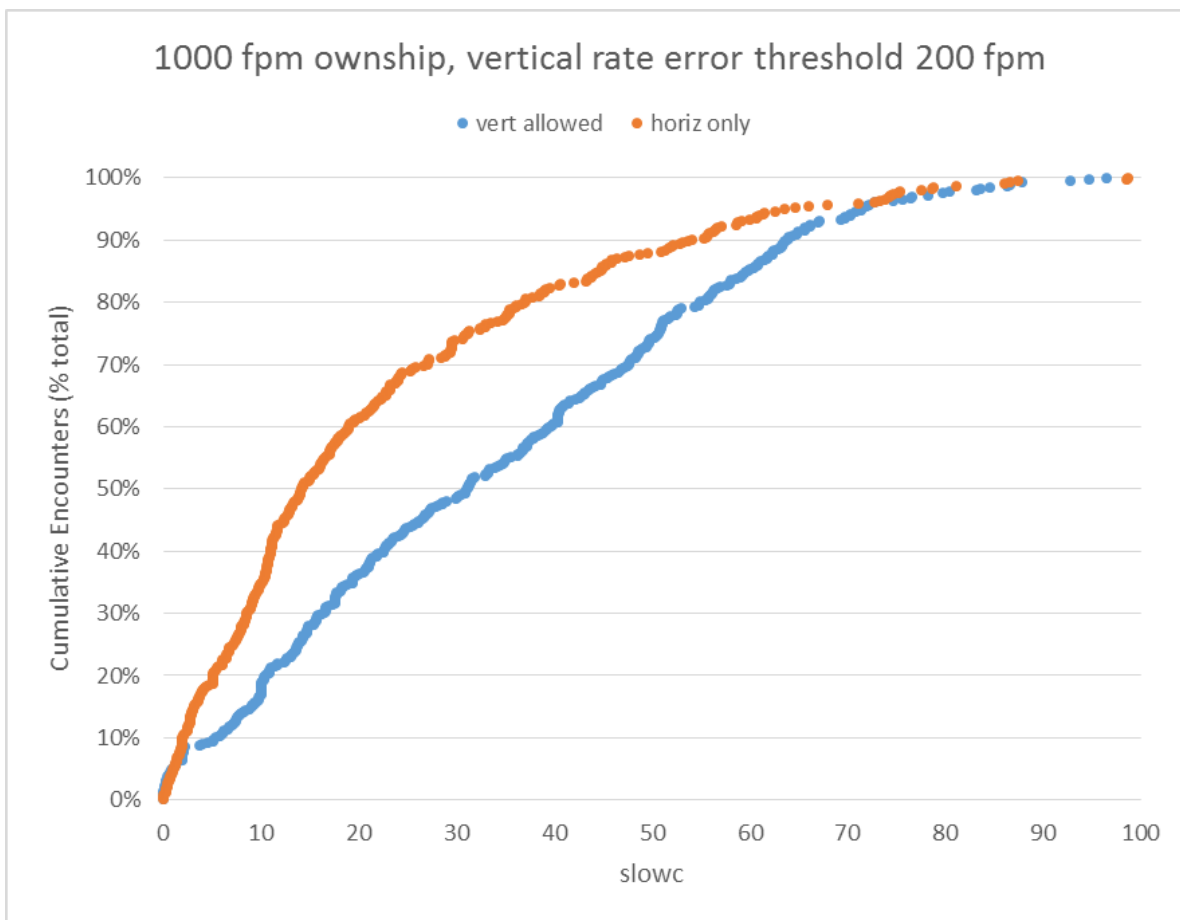
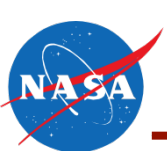
ΔT_{EX} = Pilot Execution Delay (Command and Execute Maneuver)

- Pilot response time models derived from PT5 and mini-HITL experiment data
- Evaluation and execution delays for well-clear recovery are constant: 3 seconds
- Pilot model selects smallest guidance change (plus buffer)
- Prior flight plan route/altitude Recaptured after well clear separation regained



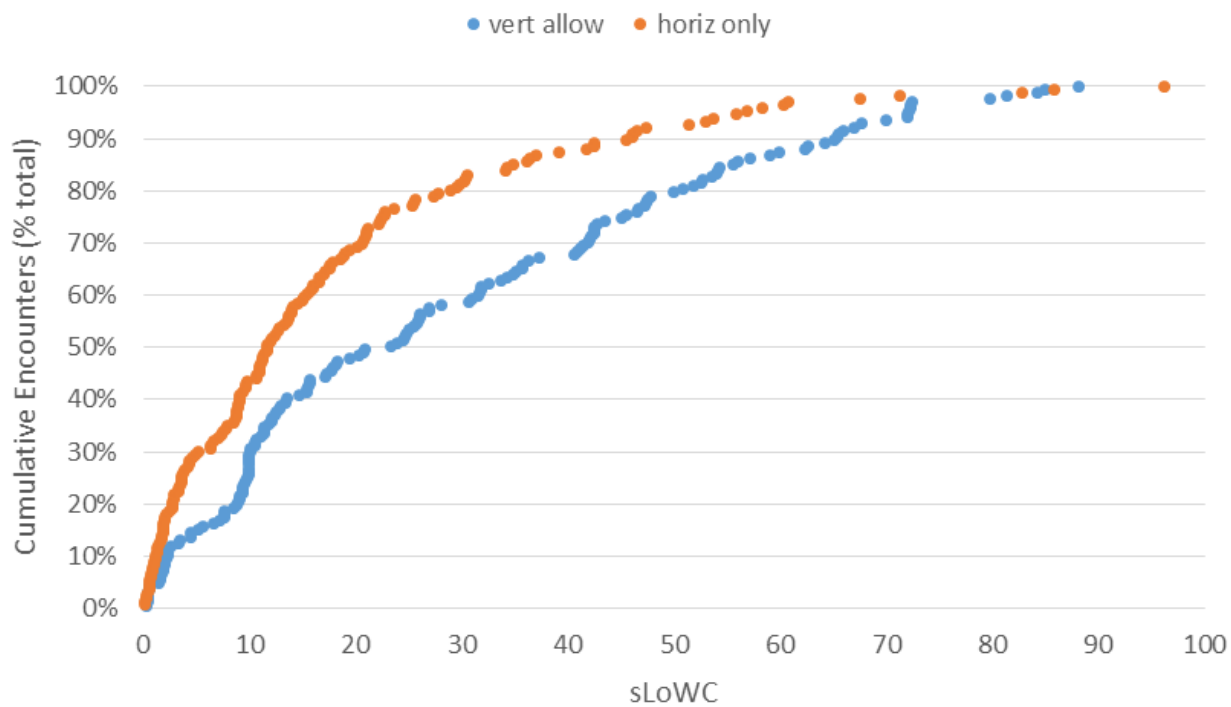
1500 fpm ownship, vertical rate error threshold 200 fpm

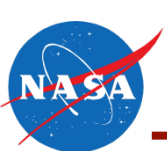




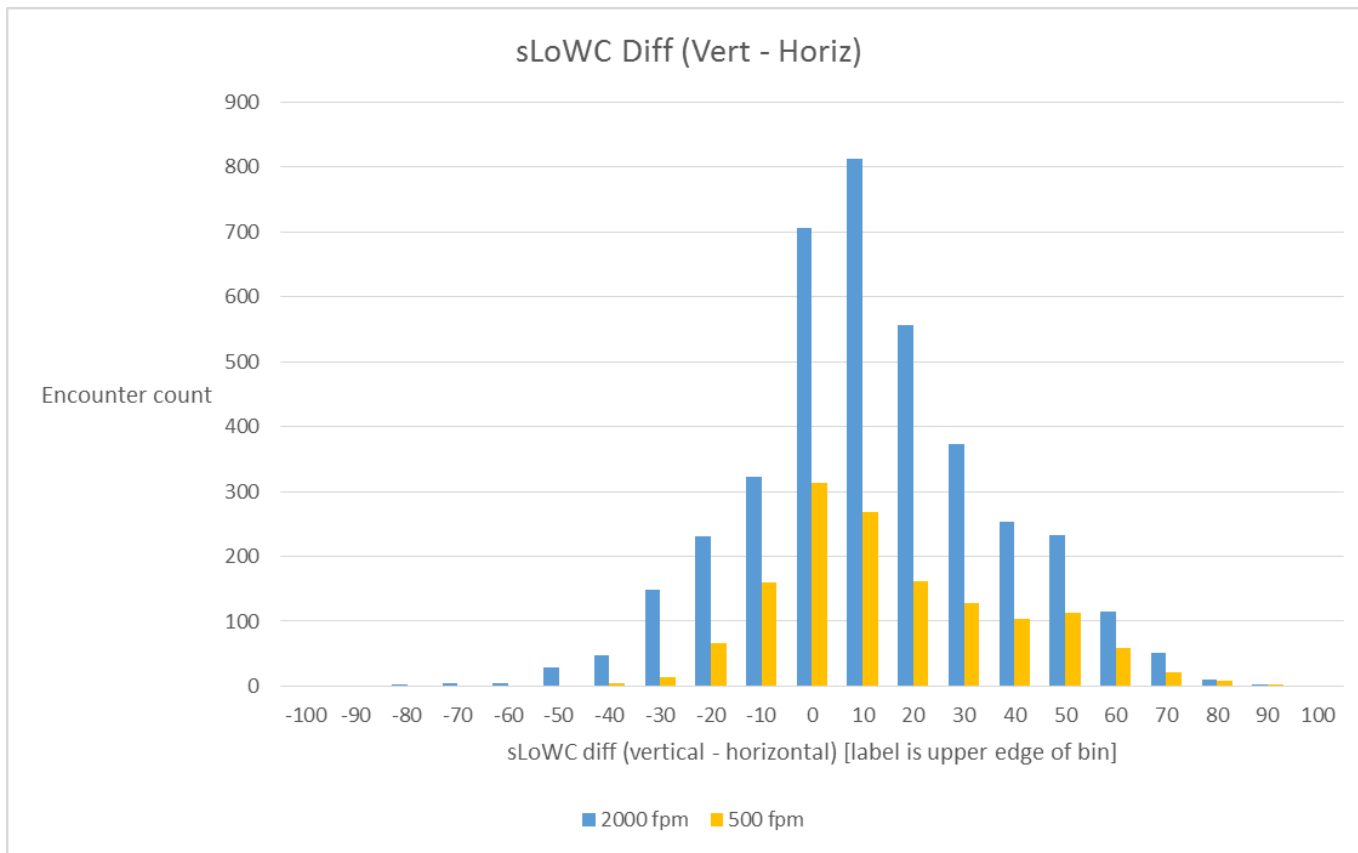


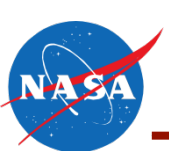
500 fpm ownship, vertical rate error threshold 200 fpm



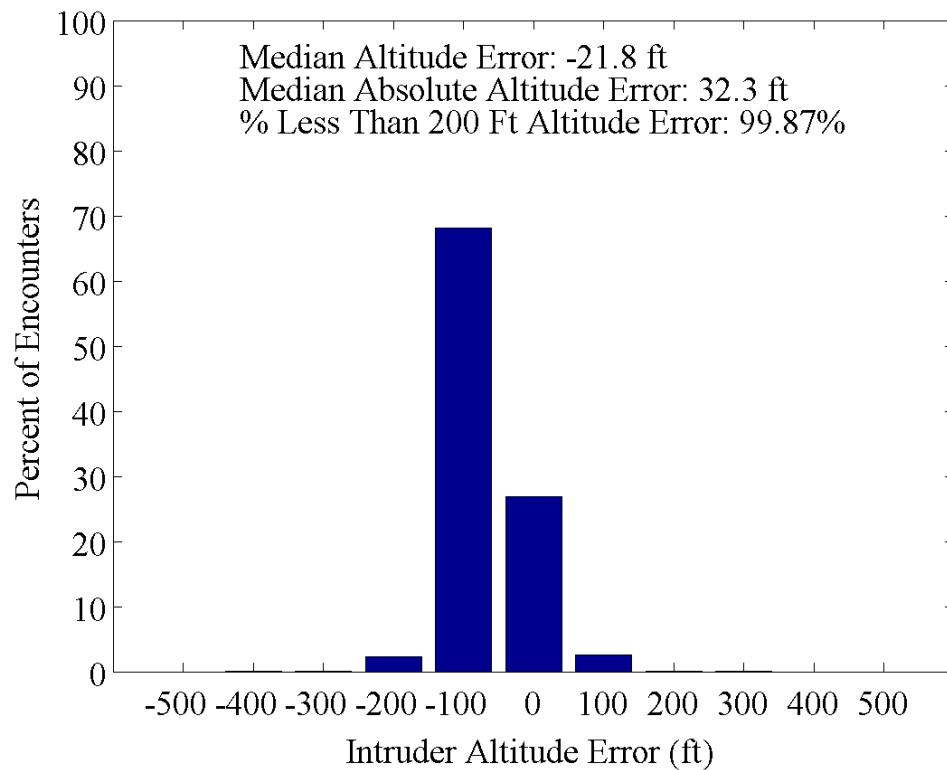


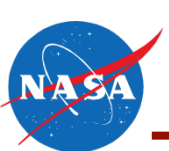
Change in sLoWC per encounter





All altitude errors, per encounter, at execution





All vert speed error, per encounter, at execution

